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THE MECHANISM OF EXPLOSION INITIA- TIONS IN THE STANDARD IMPACT SENSITIVITY TESTER

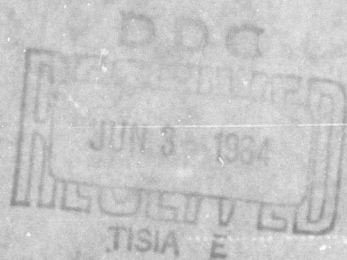
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FOREWORD

This is the final report prepared under Air Force Contract AF 04(611)-9063 and covers the period from March 1963 through February 29, 1964.

The objective of this program was to study the mechanism of explosion initiation in the standard impact sensitivity tester.

The work was administered under the direction of the Air Force Rocket Propulsion Laboratory, Mr. V. A. Moseley, Project Engineer.

ABSTRACT

Experimental impact sensitivity data have been obtained for normal propyl nitrate as the condensed phase with gas bodies consisting of the single component systems - Argon, Helium, Nitrogen, Freon-12; binary systems - (Helium-Oxygen), (Nitrogen-Oxygen), (Freon-12 - Oxygen); and the ternary system - (Freon-12/He - Oxygen).

The experimental program has separated (for the first time) the effects of heat capacity ratio, thermal conductivity, and chemical reactivity of the gas body on the impact sensitivity. Based upon a theoretical model of initiation proposed, the impact sensitivity of n-propyl nitrate has been correlated with the thermal diffusivity of the entrapped gas body. The correlation correctly predicts that Argon, Nitrogen, and Freon-12 gas bodies require energies above 92 Kg-cm for initiation to occur. The effect of chemical reactivity of the gas body is also accounted for.

TABLE OF CONTENTS

	Page
Foreword	
Abstract	iii
List of Symbols	v
I. Introduction	1
II. Experimental	6
III. Analytical Model	16
IV. Conclusions	20
V. Bibliography	23
Appendixes	
I. Calibration Data	26
II. Impact Sensitivity Data	28

LIST OF SYMBOLS

c_p	specific heat
E	activation energy
P	pressure
Q	heat of reaction
R	universal gas constant
T	temperature
t	time
u	velocity
x, X	distance
Z	collision number
α	thermal diffusivity
γ	specific heat ratio
λ	latent heat of vaporization
ρ	density

Subscripts

l	liquid
g	gas
b	boiling
1	initial
2	final

I. INTRODUCTION

The adoption of the Olin-Mathieson Drop-Weight Tester as a recommended test by the Joint Army-Navy-Air Force Panel on Liquid Propellant Test Methods has resulted in widespread usage of the instrument for evaluating the sensitivity of liquid propellants to impact. This widespread usage has developed in spite of a basic criticism of the instrument--the inability to establish the fundamental significance of the test or even to correlate the impact sensitivity with any basic physico-chemical property of the propellant.

Impact testing is a simple and rapid means for ranking materials according to explosion hazard. In the standard test, a sample of the liquid propellant is placed in a cup which is fitted with an O-ring. A 0.016 inch thick stainless steel diaphragm is placed on the O-ring and a vented piston supports a steel striker ball. Impact is delivered to the ball by a freely falling weight. The impact energy is increased until an explosion occurs and the diaphragm ruptures. Reproducibility has been a basic problem with impact testers in the past due to insufficient confinement of the sample and gas volumes in the sample cavity i.e., leakage around the O-ring before rupture. To obtain a meaningful statistical result, the requisite number of determinations lies between 10 and 30; below 10 measurements additional results strongly influence the mean while above 30 measurements additional results have little influence on the statistical average.

The usual approach has been to use the up and down technique of testing and to make about 20 determinations.

Advantages attributed to the Olin-Mathieson Drop-Weight Tester are:

1. Safe - a convenient laboratory tool for evaluating the handling characteristics of new or unknown materials.
2. Rapid - a complete determination can be made in one hour (if sufficient sample holders and air conditioned facilities are available).
3. Inexpensive - low material cost per test.
4. Simple Installation - no special mountings are required.
5. Adaptable - can be used for testing solids, slurries, and liquids.

It may be concluded that these claims are justified in the normal sense; however, the adoption of a $68 \pm 2^{\circ}\text{F}$ testing temperature introduces a complication in that an air conditioned space maintained at 68°F is necessary for volume testing. The adoption of 25°C as a standard testing temperature would have been a more judicious choice since this could be obtained a good percentage of the time without refrigeration equipment and would be in line with current trends in reporting other physico-chemical data.

Investigations of the mechanism of the impact initiation process have been carried out since World War II by a large number of investigators [2,3,5,6,8,9,10,12,13,15,19,21,23,24,25]. It has been found that the initiation process occurs within an interval

of the order of 10^{-4} seconds [2]; the time to initiation represents (a) an initial delay (before any visible reaction), (b) the propagation of a slow flame at velocities of 10-50 meters/sec, and (c) the explosion. The explosion may propagate at velocities of several meters per second or may develop into low order detonation and propagate up to 2 kilometers/sec.

The basic premise upon which initiation theory is developed is that the propellant is raised rapidly to some high temperature; Bowden proposes [3] that this may be accomplished by any of the following processes:

- (1) Adiabatic compression of an entrapped gas body.
- (2) Simple heating.
- (3) Frictional hot spot on the confining surface or on a grit particle.
- (4) Intercrystalline friction of the explosive itself (solid).
- (5) Viscous heating of the explosive at high rates of shear.
- (6) Heating at a sharp point when it is deformed plastically.
- (7) Material reinforcement of gentle shock waves.
- (8) Ultrasonic vibration.
- (9) Electrons, α particles, neutrons, etc.
- (10) Light emission of sufficient intensity.
- (11) Electric discharge.
- (12) Spontaneous initiation of a growing crystal.

Bowden and Yoffe [2] have further proposed that the mechanism of initiation in liquid explosives by impact is due to the formation of local "hot spots" rather than homogeneously throughout the body of the sample. The "hot spots" are raised to a high temperature by the unequal distribution of the energy of impact. Their experiments using grit particles with melting points between 400° and 600°C show that "hot spot" temperatures of about 500°C are necessary to initiate explosions [6].

The exact mechanism of formation of the "hot spots" may not always be the same since several processes are possible and one or more might operate simultaneously. Probably the most likely (or usual) mechanism for "hot spot" production in liquids is the rapid compression of entrapped gas bodies. (The simple act of transfer of the liquid propellant from one container to another will entrap some air; further there exists the possibility of absorption of minute quantities of air, CO₂, etc. upon standing and subsequent release of microscopic bubbles upon cooling slightly.) Also with some types of testing equipment, bubbles may be entrapped by microscopic cavities in the striker at the instant of impact.

Whether the hot spot grows into a large scale explosion or dies out is determined by the strength of the impact, physical state of the system, thermodynamic properties of the materials and kinetics of the decomposition reaction. Johansson and Selberg indicate that the increase in temperature around a gas body due to heating from the compressed gas is only a fraction of that due

to the gas temperature rise and for ignition to occur droplets must be dispersed into the gas phase [16].

The classical theory of initiation by adiabatic compression as proposed by Bowden and Yoffe [2] provides a mechanism whereby a "hot spot" may develop in the liquid phase. An examination of the impact data for various gas bodies reported in the literature shows that the classical theory fails to provide the information as to whether a given material under a given impact conditions will be more or less sensitive than another material subjected to the same conditions.

The actual mechanism appears to be much more complex, involving heat transfer, thermodynamic properties of the entrapped gas, degree of pressurization, ratio of gas to liquid, and hydrodynamic properties of the system.

The program reported here was undertaken to provide a clearer and more complete understanding of the mechanisms involved in impact testing of liquid propellants. A study has been made of the effect of heat capacity ratio, thermal conductivity and chemical reactivity of the gas body on the impact sensitivity of normal propyl nitrate.

II. EXPERIMENTAL INVESTIGATION

Equipment:

A. Drop-Weight Tester

An Olin-Mathieson Drop-Weight Tester, Model 830-700, was supplied by the Air Force. Figure 1 shows the general appearance of the unit while Figure 2 shows details of the sample cup assembly. The sample cup is fitted with a rubber O-ring for sealing purposes. The liquid sample is confined in the cavity formed by the steel cup, the rubber O-ring, and a stainless steel diaphragm placed over the O-ring. A piston which fits smoothly inside the sample cup rests on the diaphragm. The piston has a vent hole to relieve the pressure in the assembly when explosion occurs. A steel ball sits on the piston and extends outside the assembly so that the striker can drive it downward thereby forcing the piston into the sample cavity.

The volume of sample placed in the cavity is critical. The volume of the sample cavity is fixed so that variations in the amount of sample must result in variations in the gas body size. The total heat released in the bubble during compression is a function of the initial volume since the energy absorbed by the bubble equals the work done on the system, i.e., $P\Delta V$. A standard quantity of sample was used throughout all tests; a fixed stroke Hamilton Microliter syringe with a Chaney adaptor was used to deliver the sample. An accuracy of 0.01% liquid discharge was possible.

The components of the complete cup assembly are shown in Figure 3.

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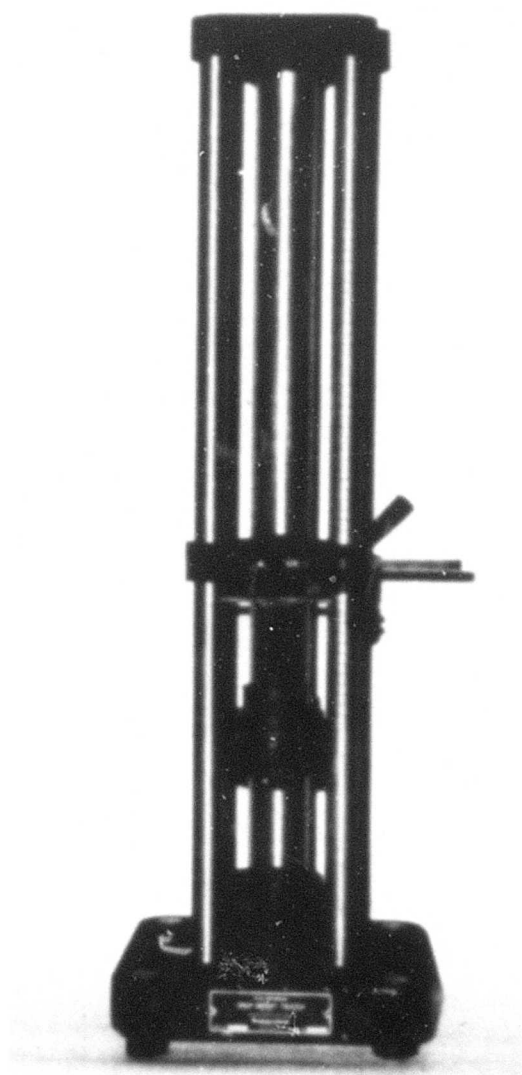


Figure 1. Impact Tester

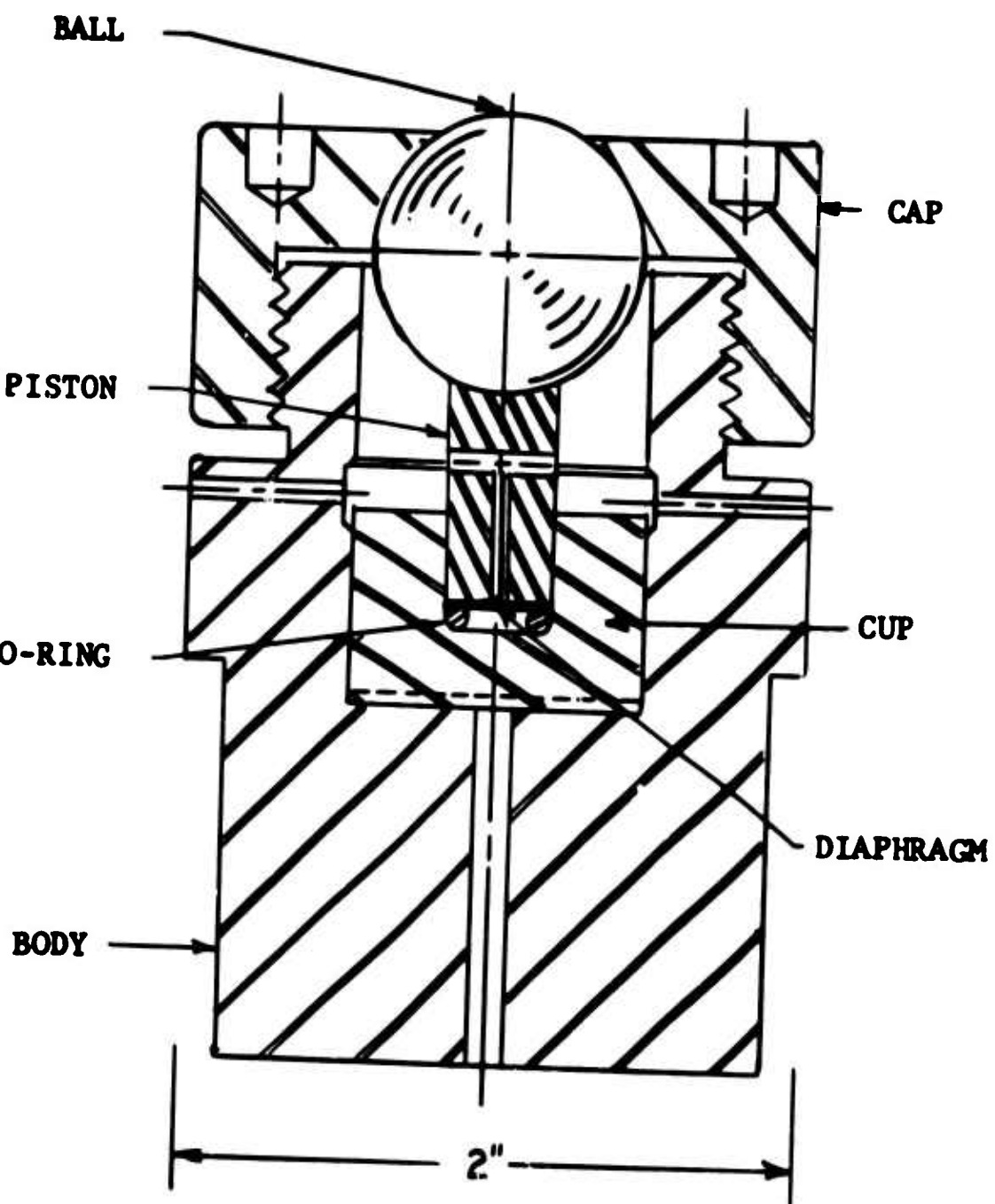


Figure 2. Schematic of Cup Assembly

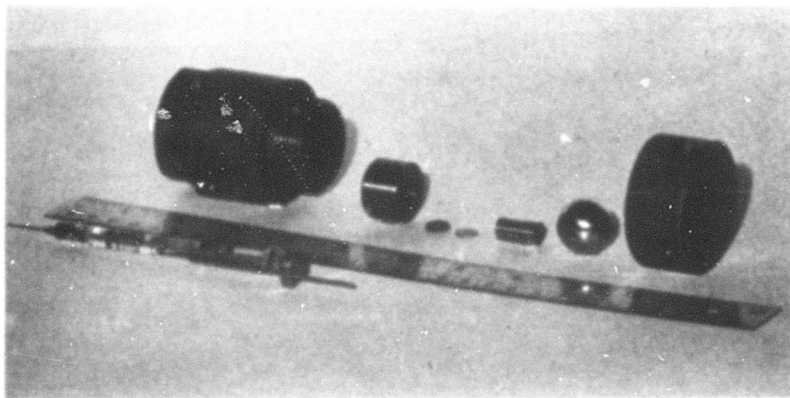


Figure 3. Cup Assembly

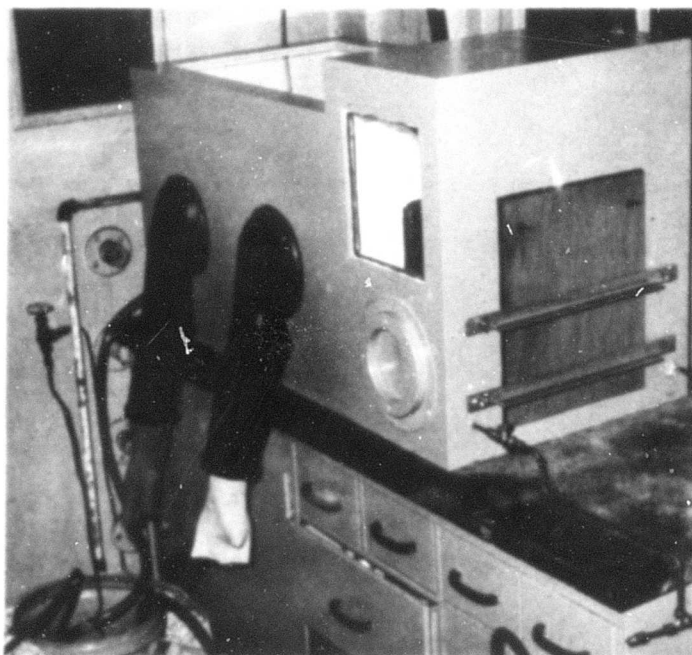


Figure 4. Atmosphere Box

B. Atmosphere Box

A controlled atmosphere box was used for filling the sample cup assemblies under the various gaseous atmospheres. The box (shown in Figure 4) was constructed of 3/4" plywood. It has two compartments. The main compartment, which was used for loading and assembling the sample cup assemblies, is fitted with rubber sleeves and gloves. A window across the top provides for visual observation of the loading operation. A smaller compartment was used as an evacuation chamber with access door on either side to provide for transfer of samples in and out of the main compartment without contamination of the atmosphere or undue loss of the atmosphere. Weather balloons were used as positive displacement devices for changing atmospheres; the balloons were filled with compressed air until the box was essentially filled. Then fresh gas of the atmosphere being used was admitted to the box directly from a premixed tank as the balloons were allowed to collapse. The box was designed to operate under a slight positive pressure (1 to 2" water) to insure that no air entered the system.

C. Temperature Control Circuit

The standard test procedure calls for testing to be performed at $68 \pm 2^{\circ}\text{F}$. The control circuit consisted of an oil bath, containing Hy-Vac vacuum pump oil (low vapor pressure) which was placed inside the main compartment of the atmosphere box (internal oil bath) and connected to an external ice bath. Oil circulated from the internal bath through a coil which was

immersed in the external ice bath and thence back to the internal bath. A copper tray immersed in the internal oil bath received the sample cup assembly.

Time temperature histories of the cup assembly were measured after placement in the bath in order to determine the time required for thermal equilibrium to be attained. Approximately 25 minutes were required to bring the cup assemblies to 69°F when the oil bath was cooled to 65°F. The handling procedure was also important since the sample cups had to be transferred from the oil bath to the drop-weight tester. Time temperature histories were compared for three procedures.

The first technique was to measure the change in temperature of the cup assembly when standing in the room at 77°F; the rate of temperature rise was found to be 0.1°F/min. The second procedure was to grasp the cup assembly by the cap between the thumb and index finger; the rate of temperature change increased to 0.7°F/min. Finally the cup assembly was held firmly in the palm of the hand; the rate of temperature change in the cup jumped to 2.3°F/min. This data is shown in Figure 5.

Sample cooling was achieved in much the same manner. Approximately 30 cc of liquid sample were poured into a 50 cc flask which was placed in the copper tray holder. Twenty-five minutes were required for the sample to reach 69°F; the minimum temperature finally reached was 67°F. The flask was kept in the tray at all times thereafter.

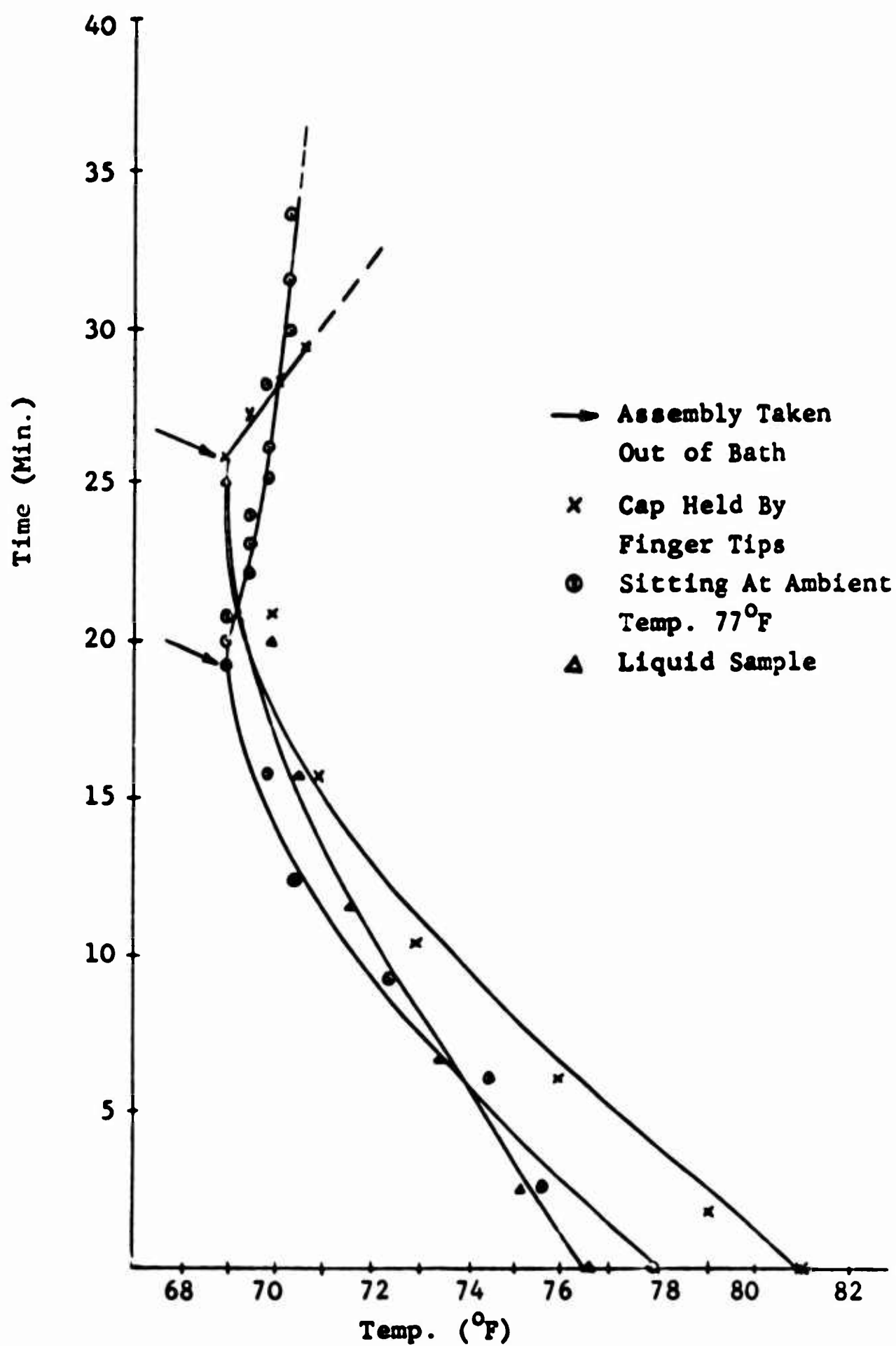


Figure 5. Cooling Curves

The standard loading and handling procedure adopted was to cool the sample cup assembly to 69°F and then to load with pre-cooled sample. The loaded cup assembly was transferred to the tester rapidly and impacted immediately.

D. Properties of Materials

N-propyl nitrate was obtained from Eastman Organic Chemicals. It was purged with nitrogen gas (99.996% purity) for ten hours to remove traces of oxygen and then stored with a blanket of nitrogen over the liquid. Gases were purchased from the Mathieson Company as follows:

Argon		99.998% Min Purity
Helium		99.99% Min Purity
Nitrogen	Extra dry grade	99.7% Min Purity
Oxygen	Extra dry grade	99.6% Min Purity
Freon-12		99.0% Min Purity

No further purification was attempted.

E. Calibration of the Apparatus

The standard procedure for calibration of the instrument was to determine the impact energy required to produce hydraulic rupture of the stainless steel diaphragm. The 50% probability point was determined for the water rupture value under the same conditions used in propellant testing. The value obtained established the upper working limit for the particular diaphragm since rupture occurs at this point irrespective of the explosive ability of the material being tested. A normal value of 140 Kg-cm has been reported by the manufacturer; 85% of this maximum value is

then used in practice so that rupture actually signifies an explosion has taken place.

The instrument used in this work was calibrated in the standard way. Calibration data are included in Appendix I. The data are compared in Figure 6 with those data reported in JANAF Test Methods #4. Values obtained ranged from 108.1 Kg-cm to 108.5; these are lower than those shown in JANAF Test Methods #4 but are more nearly constant values (129 to 148 for JANAF data). The upper limit for testing was then established at 92 Kg-cm.

Measurements of diaphragm size and thickness as well as O-ring dimensions by optical comparator showed that these were within specified limits. These data are included in Appendix I. In view of these results it was concluded that the 108 Kg-cm hydraulic rupture was correct for the instrument. This calibration was obtained several times throughout the course of the work.

F. Test Procedure

All tests were run in accordance with the procedure recommended by the JANAF Test Methods #4 (p. 4).

Step 1 Clean all components of the cup assembly with acetone and wipe dry with a soft tissue. Vent holes must be kept clean.

Step 2 Set required weight and height on the impact tester.

Step 3 Place an O-ring in the bottom of the cup and make sure it is seated firmly.

Step 4 Carefully inject 0.03 cc of liquid sample into the cavity with a fixed stroke syringe.

Step 5 Slide a diaphragm across the top surface of cup so that it drops flat onto the O-ring.

Step 6 Place the piston in the cup.

Step 7 Place the cup in the assembly.

Step 8 Place the ball on top of the piston.

Step 9 Screw the cap on the body and tighten with a torque wrench to 7 inch-pounds.

Step 10 Place body in retainer of the impact tester.

Step 11 Release the weight and record result.

Step 12 Discard diaphragm and O-ring and clean as in Step 1.

The energy required for initiation of explosion is not a sharply defined point with the impact tester; however, the occurrence of explosion follows a normal distribution over the range of energy levels. The sensitivity value reported is the mean value or the point of 50% probability of an explosion occurring. The 50% point (E_{50}) was readily established by making a number of determinations; the up and down procedure was found to be convenient. The 50% point was bracketed by changing the energy level after each test. When the test was positive the weight was decreased; when it was negative the weight was increased.

Drop heights of 10 and 20 centimeters were used in these experiments. When 20 tests had been performed, the 50% point was computed by a simple statistical analysis of the distribution of test results. This sample calculation is shown in Appendix II. The raw experimental data are recorded in Appendix II and summarized in Table 1 below.

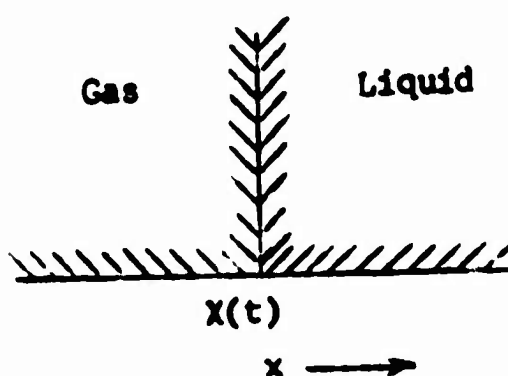
TABLE 1

IMPACT SENSITIVITY DATA FOR NORMAL PROPYL NITRATE

Gas Body		Sample	E ₅₀
Inert	Oxygen %	Temp °F	Kg-cm
Argon	None	71	above 92
Helium	None	69	60.90
Helium	4	69	59.35
Helium	13	69	50.15
Helium	17	69	30.15
Helium	21	69	15.02
Helium	50	69	13.10
Nitrogen	0	69	above 92
Nitrogen	4	69	above 92
Nitrogen	13	69	83.80
Nitrogen	17	69	59.70
Nitrogen	21	69	16.95
Nitrogen	50	69	16.53
Freon	None	69	above 92
Freon	18	69	above 92
Freon	21	69	above 92
Freon	50	69	above 92
Freon/He (10/73)	None	69	72.85
Freon/He	13	69	62.65
Freon/He	17	69	39.00
Freon/He	21	69	29.63
Freon/He	50	77	9.45
A59.6%/He40.4%	None	69	78.3
	Air	70.5	16.95
	Air	77.0	15.13
	Air	99.0	11.75

III. ANALYTICAL MODEL

The ideal analytical model is that of a single spherical gas bubble immersed in an infinite reservoir of the liquid propellant. A series of events is postulated to take place when the system is subjected to impact: (1) the gas-liquid interface moves in as the bubble is compressed; (2) the gas temperature rises due to compression; (3) reaction occurs at an increasing rate; (4) vaporization occurs at the gas-liquid interface and the interface recedes as explosion occurs. For simplicity it is assumed that the impact occurs instantaneously; this is equivalent to stating that the gas body is suddenly subjected to a step in temperature. Further consider the problem in one dimension: Let ρ_g , C_{pg} , k_g , and α_g be the thermal constants and T_{g1} be the temperature of the gas phase; also let ρ_l , C_{pl} , k_l , and α_l be the thermal constants and T_{l2} be the temperature of the liquid phase.



Suppose λ is the latent heat of vaporization and T_b the boiling point of the liquid propellant; if the surface of separation between the gas and liquid phases is at $X(t)$, one boundary condition to be satisfied at this surface is $T_{gl} = T_l = T_b$ when $x = X(t)$.

The second boundary condition concerns the adsorption of latent heat at this surface. The region $x > X(t)$ contains liquid at temperature $T_l(x,t)$ and the region $x < X(t)$ contains gas at temperature $T_g(x,t)$. When the surface moves a distance dx , a quantity of heat $\lambda \rho_l dx$ is absorbed and must be supplied by conduction.

This requires:

$$\rho_g \frac{\partial T_g}{\partial x} - \frac{\rho_l \partial T_l}{\partial x} = \lambda \rho_l \frac{dX}{dt} \quad (1)$$

In the gas and liquid phases, the temperatures must satisfy:

$$\frac{\partial^2 T_l}{\partial x^2} - \frac{1}{\alpha_l} \frac{\partial T_l}{\partial t} = 0 \quad (2)$$

$$\frac{\partial^2 T_g}{\partial x^2} - \frac{1}{\alpha_g} \frac{\partial T_g}{\partial t} = 0 \quad (3)$$

At the same time the gas-liquid interface moves out, there will be motion of the gas away from the interface. The evaporated mass of liquid, $\rho_l dX$, generates a gas layer of thickness X . Thus the velocity of the gas moves along the X -axis:

$$u_g = \frac{dX}{dt} - \frac{\rho_l}{\rho_g} \frac{dX}{dt} \quad (4)$$

A complete description of the system is given by the simultaneous solution of equations (2), (3), and (4). This has not been possible in the time available. Examination of equations (1) and (3) led to the conclusion that the controlling factor in the equations was the thermal diffusivity of the gas phase for a given liquid propellant. It was then postulated that the impact energy for initiation could be correlated with the thermal diffusivity of the gas. This has been done in Figure 6 where the mean impact energy (E_{50}) has been plotted versus the thermal diffusivity of the entrapped gas body for the series of gases tested in the experimental program. Clearly a correlation exists.

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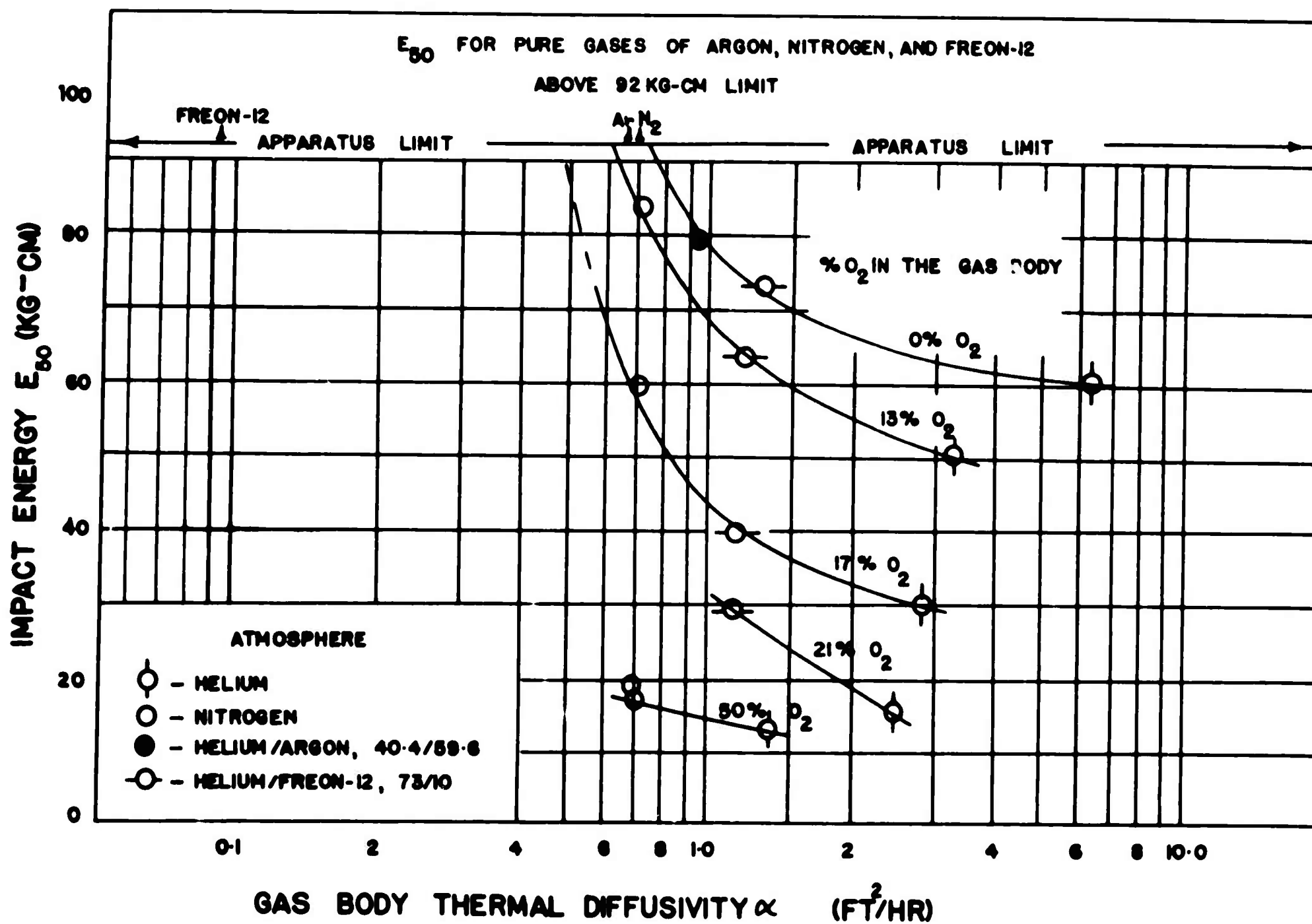


Figure 6. Effect of Thermal Diffusivity and Chemical Reactivity of the Entrapped Gas Bubble on Impact Energy for Initiation.

IV. CONCLUSIONS

An analysis of the impact data reported in the literature shows that initial pressure of the gas body is universally important. This is in agreement with the classical theory which postulates that initiation is due to adiabatic compression of entrapped gas bodies:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

The equation states that an increase in the initial pressure at a given pressure ratio increases the final temperature; likewise an increase in the initial temperature for a given pressure ratio increases the final temperature and the higher the final temperature the more likely the explosion. This is about all that can be concluded from the classical theory. Clearly an additional mechanism is needed.

The mechanism proposed retains the "hot spot" concept but relaxes the adiabatic requirements and considers the thermal characteristics of the entrapped gas. Under conditions of impact the temperature of the entrapped gas body rises rapidly and essentially adiabatically creating a "hot spot" or kernel.* Some chemical reaction also occurs during the compression step (some propellant is present in the gas phase due to vapor pressure and some droplets or ligaments are probably dispersed into the gas phase when impact occurs), and this increases the kernel

*Classical theory implies further that it occurs isentropically but this is not necessarily so since shock waves probably develop.

temperature. The hot gas body vaporizes liquid propellant at the gas-liquid interface. For an explosion to progress throughout the system, sufficient heat must be supplied by the initial kernel to vaporize and heat to ignition temperature the differential shell of liquid surrounding it; this shell burns and liberates heat to continue the process in the next shell and so on. The vaporization process requires a large amount of energy; this energy must initially come from the "hot spot." Therefore the rate of heat transfer through the gas body must be sufficiently large to accommodate the initial vaporization process. If the heat is transferred by pure conduction, then the rate of transfer is determined by the thermal diffusivity of the gas body for a given liquid system. The thermal diffusivity of the gas body, then, may be used as a means for ranking the sensitivity of a given liquid propellant to various inert atmospheres. The higher the thermal diffusivity of the gas bubble, the greater the sensitivity of the liquid to impact. If a given liquid propellant is subjected to impact under two different atmospheres of the same thermal diffusivity, the more reactive one will initiate explosion at the lower impact level.

These conclusions are borne out in Figure 6. On the basis of the correlation it is predicted that each of the pure gases Argon, Nitrogen, or Freon-12 would have E_{50} values above the 92 Kg-cm limit established for the drop-weight tester used. This was found to be the case experimentally. The data also illustrates again the inadequacy of the classical theory since

Helium and Argon both have heat capacity ratios of 1.67 and are inert gases. Helium however, initiates explosion readily whereas Argon does not. The correlation correctly confirms this also.

The same reasoning applied in the liquid phase; here however, the lower the thermal diffusivity the more sensitive the system should be - a high thermal diffusivity would dissipate the energy into the liquid without vaporizing and igniting the interface.

The effect of chemical reactivity is also shown on Figure 6. Curves of constant percent oxygen show that increasing oxygen content (i.e., increasing chemical reactivity of the mixture) in the gas body increases the sensitivity to impact. This is readily explained by the fact that the hot spot temperature (as well as shells subsequently ignited) will be increased by increased oxygen concentration in the gas phase up until a stoichiometric mixture results. Further increases in oxygen concentration would then have about the effect of additional nitrogen since the thermal diffusivities are so close.

In conclusion a mechanism of initiation has been proposed which leads to a correlation of impact sensitivity with thermal diffusivity of the entrapped gas body and the correlation correctly predicts the sensitivity to initiation of explosion by an entrapped gas body.

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DISTRIBUTION

This report is distributed to the Chemical Propulsion Mailing List of December 1963, Categories 1 and 3.

APPENDIXES I AND II

APPENDIX I

CALIBRATION DATA

TABLE 2

CALIBRATION DATA FOR DROP-WEIGHT TESTER

Temp. 69°F

Test No.	Ht. (cm)	Wt. (kg)	E(kg-cm)	Result
1	35	3.0	105	-
2	"	3.2	112	-
3	"	3.4	119	+
4	"	3.2	112	+
5	"	3.0	105	-
6	"	3.2	112	+
7	"	3.0	105	+
8	"	2.8	98	-
9	"	3.0	105	-
10	"	3.2	112	+

$E_{50} = 108.5$ kg-cm at 35 cm.

1	25	4.2	105	-
2	"	4.4	110	+
3	"	4.2	105	-
4	"	4.4	110	+
5	"	4.2	105	-
6	"	4.4	110	+
7	"	4.2	105	-
8	"	4.4	110	+
9	"	4.2	105	-
10	"	4.4	110	-

$E_{50} = 108.125$ kg-cm at 25 cm.

1	20	5.4	108	+
2	"	5.2	104	-
3	"	5.4	108	+
4	"	5.2	104	-
5	"	5.4	108	+
6	"	5.2	104	-
7	"	5.4	108	-
8	"	5.6	112	-
9	"	5.8	116	+
10	"	5.6	112	-

$E_{50} = 108.4$ kg-cm at 20 cm.

TABLE 3

a.) O-ring Measurements taken from JANAF Book.

.239 \pm .005 inch I.D..379 \pm .003 inch O.D.

Measured:	O.D. (in)	I.D. (in)	Thickness (in)
1	.3867	.2406	.0686
2	.3870	.2393	.0693
3	.3872	.2398	.0706
4	.3855	.2401	.0688
5	.3838	.2401	.0690
6	.3858	.2379	.0712
7	.3877	.2419	.0714
8	.3842	.2445	.0696
9	.3848	.2430	.0709
10	.3845	.2384	.0717

b.) Diaphragm Measurement taken from JANAF Book.

.015 inch thick

.363 inch Dia.

Measured:	Thickness (in)	Dia. (in)
1	.0154	.3641
2	.0155	.3641
3	.0147	.3643
4	.0149	.3638
5	.0155	.3640
6	.0146	.3648
7	.0155	.3646
8	.0150	.3640
9	.0157	.3645
10	.0155	.3639

APPENDIX II

IMPACT SENSITIVITY DATA

TABLE 4

NPN (Normal Propyl Nitrate)

Pure Helium

Sample Volume .03cc

Sample Temperature 69°F

Ambient Temperature 73°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	20	2.90	58	-
2	"	2.95	59	+ *
3	"	2.90	58	-
4	"	2.95	59	-
5	"	3.00	60	-
6	"	3.05	61	+
7	"	3.00	60	-
8	"	3.05	61	+
9	"	3.00	60	-
10	"	3.05	61	+
11	"	3.00	60	-
12	"	3.05	61	-
13	"	3.10	62	-
14	"	3.15	63	+
15	"	3.10	62	-
16	"	3.15	63	+
17	"	3.10	62	-
18	"	3.15	63	+
19	"	3.10	62	+
20	"	3.05	61	-

*Burn, smell, smoke but no rupture

Arithmetic mean: $2 \times 58 = 116$
 $2 \times 59 = 118$
 $4 \times 60 = 240$
 $5 \times 61 = 305$
 $4 \times 62 = 248$
 $3 \times 63 = 189$
1216

$$\frac{1216}{20} = 60.80$$

$$E_{50} = 60.80 \text{ kg-cm}$$

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TABLE 4 (cont'd)

NPN

4 mole % O₂ and He

Sample Volume .03 cc
 Sample Temperature 69°F
 Ambient Temperature 87°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	20	2.50	50	-
2	"	2.70	54	-
3	"	2.90	58	-
4	"	2.95	59	+
5	"	2.90	58	-
6	"	2.95	59	+
7	"	2.90	58	-
8	"	2.95	59	+
9	"	2.90	58	-
10	"	2.95	59	+ *
11	"	2.90	58	-
12	"	2.95	59	-
13	"	3.00	60	-
14	"	3.05	61	+
15	"	3.00	60	-
16	"	3.05	61	+
17	"	3.00	60	-
18	"	3.05	61	+
19	"	3.00	60	+
20	"	2.95	59	-

$$E_{50} = 59.35 \text{ kg-cm}$$

NPN

13 mole % O₂ and He

Sample Volume .03 cc
 Sample Temperature 69°F
 Ambient Temperature 88°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	20	2.50	50	-
2	"	2.60	52	-
3	"	2.65	53	+
4	"	2.60	52	+
5	"	2.55	51	-
6	"	2.60	52	+
7	"	2.55	51	-
8	"	2.60	52	+
9	"	2.55	51	+
10	"	2.50	50	+
11	"	2.45	49	+
12	"	2.40	48	-
13	"	2.45	49	+
14	"	2.40	48	-
15	"	2.45	49	+
16	"	2.40	48	-
17	"	2.45	49	-
18	"	2.50	50	+
19	"	2.45	49	-
20	"	2.50	50	+

$$E_{50} = 50.15 \text{ kg-cm}$$

*Burn, smell, smoke but no rupture.

TABLE 4 (cont'd)

NPN

17 mole % O₂ and He

Sample Volume .03 cc

Sample Temperature 69°F

Ambient Temperature 78°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	20	1.50	30	-
2	"	1.70	34	+
3	"	1.60	32	-
4	"	1.65	33	+ *
5	"	1.60	32	+ *
6	"	1.55	31	+ *
7	"	1.50	30	+
8	"	1.45	29	-
9	"	1.50	30	+
10	"	1.45	29	-
11	"	1.50	30	-
12	"	1.55	31	+
13	"	1.50	30	-
14	"	1.55	31	+
15	"	1.50	30	+
16	"	1.45	29	+
17	"	1.40	28	-
18	"	1.45	29	+
19	"	1.40	28	-
20	"	1.45	29	+

$$E_{50} = 30.15 \text{ kg-cm}$$

*Burn, smell, smoke but no rupture

NPN

21 mole % O₂ and He

Sample Volume .03 cc

Sample Temperature 69°F

Ambient Temperature 86°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	10	1.40	14.0	-
2	"	1.60	16.0	+ *
3	"	1.50	15.0	+ *
4	"	1.45	14.5	+ *
5	"	1.40	14.0	-
6	"	1.45	14.5	-
7	"	1.50	15.0	-
8	"	1.55	15.5	-
9	"	1.60	16.0	+ *
10	"	1.55	15.5	+
11	"	1.50	15.0	+
12	"	1.45	14.5	-
13	"	1.50	15.0	-
14	"	1.55	15.5	+
15	"	1.50	15.0	-
16	"	1.55	15.5	+
17	"	1.50	15.0	-
18	"	1.55	15.5	+ *
19	"	1.50	15.0	+ *
20	"	1.45	14.5	-

$$E_{50} = 15.02 \text{ kg-cm}$$

TABLE 4 (cont'd)

NPN
 50 mole % O₂ and He
 Sample Volume .03 cc
 Sample Temperature 69°F
 Ambient Temperature 78.5°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	10	1.35	13.5	+ *
2	"	1.30	13.0	-
3	"	1.35	13.5	+
4	"	1.30	13.0	-
5	"	1.35	13.5	+
6	"	1.30	13.0	-
7	"	1.35	13.5	+
8	"	1.30	13.0	+ *
9	"	1.25	12.5	-
10	"	1.30	13.0	+
11	"	1.25	12.5	+
12	"	1.20	12.0	-
13	"	1.25	12.5	-
14	"	1.30	13.0	+
15	"	1.25	12.5	-
16	"	1.30	13.0	-
17	"	1.35	13.5	-
18	"	1.40	14.0	+ *
19	"	1.35	13.5	-
20	"	1.40	14.0	+

$$E_{50} = 13.10 \text{ kg-cm}$$

NPN
 4 mole % O₂ and N₂
 Sample Volume .03 cc
 Sample Temperature 69°F
 Ambient Temperature 76°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	20	4.6	92	-
2	"	4.6	92	-
3	"	4.6	92	-
4	"	4.6	92	-
5	"	4.6	92	-
6	"	4.6	92	-
7	"	4.6	92	-
8	"	4.6	92	-
9	"	4.6	92	-

$$E_{50} > 92 \text{ kg-cm}$$

*Burn, smell, smoke but no rupture

TABLE 4 (cont'd)

NPN

13 mole % O₂ and N₂

Sample Volume .03 cc

Sample Temperature 69°F

Ambient Temperature 75°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Results
1	20	4.00	80	-
2	"	4.30	86	+
3	"	4.25	85	+
4	"	4.20	84	+
5	"	4.10	82	+ *
6	"	4.00	80	-
7	"	4.05	81	-
8	"	4.10	82	-
9	"	4.15	83	+
10	"	4.10	82	-
11	"	4.15	83	-
12	"	4.20	84	+
13	"	4.15	83	-
14	"	4.20	84	-
15	"	4.30	86	-
16	"	4.40	88	+ *
17	"	4.35	87	+
18	"	4.30	86	+
19	"	4.25	85	-
20	"	4.30	86	-

$$E_{50} = 83.80 \text{ kg-cm}$$

NPN

17 mole % O₂ and N₂

Sample Volume .03 cc

Sample Temperature 69°F

Ambient Temperature 77°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Results
1	20	2.90	58	-
2	"	3.00	60	+
3	"	2.95	59	+
4	"	2.90	58	-
5	"	2.95	59	+
6	"	3.00	60	+
7	"	2.95	59	-
8	"	3.00	60	+
9	"	2.95	59	-
10	"	3.00	60	+
11	"	2.95	59	-
12	"	3.00	60	-
13	"	3.05	61	+
14	"	3.00	60	+
15	"	2.95	59	-
16	"	3.00	60	-
17	"	3.05	61	+
18	"	3.00	60	+
19	"	2.95	59	-
20	"	3.00	60	+

$$E_{50} = 59.70 \text{ kg-cm}$$

*Burn, smell, smoke but no rupture

TABLE 4 (cont'd)

NPN

21 mole % O₂ and N₂ (Air)

Sample Volume .03 cc

Sample Temperature 69°F

Ambient Temperature 69.5°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Results
1	10	1.60	16.0	+
2	"	1.55	15.5	-
3	"	1.65	16.5	+
4	"	1.60	16.0	-
5	"	1.65	16.5	-
6	"	1.70	17.0	+
7	"	1.65	16.5	-
8	"	1.70	17.0	-
9	"	1.75	17.5	+
10	"	1.70	17.0	-
11	"	1.75	17.5	+
12	"	1.70	17.0	+
13	"	1.65	16.5	-
14	"	1.70	17.0	-
15	"	1.75	17.5	+
16	"	1.70	17.0	-
17	"	1.75	17.5	-
18	"	1.80	18.0	+
19	"	1.75	17.5	-
20	"	1.80	18.0	+

$$E_{50} = 16.95 \text{ kg-cm}$$

NPN

50 mole % O₂ and N₂

Sample Volume .03 cc

Sample Temperature 69°F

Ambient Temperature 82.5°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Results
1	10	1.50	15.0	-
2	"	1.70	17.0	-
3	"	1.70	17.0	-
4	"	1.75	17.5	+
5	"	1.70	17.0	-
6	"	1.75	17.5	+
7	"	1.70	17.0	-
8	"	1.75	17.5	+
9	"	1.70	17.0	-
10	"	1.75	17.5	+
11	"	1.70	17.0	-
12	"	1.75	17.5	+
13	"	1.70	17.0	+
14	"	1.65	16.5	+
15	"	1.60	16.0	+
16	"	1.55	15.5	+
17	"	1.50	15.0	-
18	"	1.55	15.5	+
19	"	1.50	15.0	-
20	"	1.55	15.5	+

$$E_{50} = 16.53 \text{ kg-cm}$$

TABLE 4 (cont'd)

NPN

18 mole % O₂ and Freon 12

Sample Volume .03 cc

Sample Temperature 69°F

Ambient Temperature 82°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	20	4.6	92	-
2	"	4.6	92	-
3	"	4.6	92	-
4	"	4.6	92	-
5	"	4.6	92	-
6	"	4.6	92	-

E₅₀ > 92 kg-cm

NPN

21 mole % O₂ and Freon 12

Sample Volume .03 cc

Sample Temperature 69°F

Ambient Temperature 78°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	20	4.6	92	-
2	"	4.6	92	-
3	"	4.6	92	-
4	"	4.6	92	-
5	"	4.6	92	-
6	"	4.6	92	-

E₅₀ > 92 kg-cm

TABLE 4 (cont'd)

NPN

50 mole % O₂ and Freon 12

Sample Volume .03 cc

Sample Temperature 69°F

Ambient Temperature 80°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	20	4.6	92	-
2	"	4.6	92	-
3	"	4.6	92	-
4	"	4.6	92	-
5	"	4.6	92	-
6	"	4.6	92	-

 $E_{50} > 92 \text{ kg-cm}$

NPN

10/83 Freon 12 and 73/83 He

Sample Volume .03 cc

Sample Temperature 69°F

Ambient Temperature 76°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	20	3.70	74	+
2	"	3.60	72	-
3	"	3.65	73	-
4	"	3.70	74	+
5	"	3.65	73	+
6	"	3.60	72	+
7	"	3.55	71	-
8	"	3.60	72	+
9	"	3.55	71	-
10	"	3.60	72	-
11	"	3.65	73	-
12	"	3.70	74	+
13	"	3.65	73	-
14	"	3.70	74	+
15	"	3.65	73	-
16	"	3.70	74	+
17	"	3.65	73	-
18	"	3.70	74	+
19	"	3.65	73	+
20	"	3.60	72	-

 $E_{50} = 72.85 \text{ kg-cm}$

*Burn, smell, smoke but no rupture

TABLE 4 (cont'd)

NPN

10.5 mole % Freon 12, 13 mole % O₂ and
76.5 mole % HeSample Volume .03 cc
Sample Temperature 69°F
Ambient Temperature 76°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	20	3.30	66	+
2	"	3.20	64	+
3	"	3.15	63	+
4	"	3.10	62	-
5	"	3.15	63	+
6	"	3.10	62	-
7	"	3.15	63	+
8	"	3.10	62	-
9	"	3.15	63	+
10	"	3.10	62	-
11	"	3.15	63	+
12	"	3.10	62	-
13	"	3.15	63	+
14	"	3.10	62	-
15	"	3.15	63	-
16	"	3.20	64	+
17	"	3.15	63	+
18	"	3.10	62	-
19	"	3.15	63	+
20	"	3.10	62	-

$$E_{50} = 62.65 \text{ kg-cm}$$

*Burn, smell, smoke but no rupture

NPN

10 mole % Freon-12, 17 mole % O₂ and
73 mole % HeSample Volume .03 cc
Sample Temperature 69°F
Ambient Temperature 80°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	20	1.50	30	-
2	"	1.90	38	-
3	"	2.00	40	+
4	"	1.95	39	-
5	"	2.00	40	+
6	"	1.95	39	+
7	"	1.90	38	-
8	"	1.95	39	+
9	"	1.90	38	-
10	"	1.95	39	+
11	"	1.90	38	-
12	"	1.95	39	-
13	"	2.00	40	+
14	"	1.95	39	-
15	"	2.00	40	+
16	"	1.95	39	-
17	"	2.00	40	+
18	"	1.95	39	+
19	"	1.90	38	-
20	"	1.95	39	+

$$E_{50} = 39.00 \text{ kg-cm}$$

TABLE 4 (cont'd)

NPN

9.5 mole % Freon 12, 21 mole % O₂ and 69.5 mole % He

Sample Volume .03 cc

Sample Temperature 69°F

Ambient Temperature 80°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	10	3.20	32.0	+ *
2	"	3.10	31.0	+
3	"	3.05	30.5	-
4	"	3.10	31.0	+
5	"	3.05	30.5	+
6	"	3.00	30.0	+
7	"	2.95	29.5	+
8	"	2.90	29.0	-
9	"	2.95	29.5	+
10	"	2.90	29.0	-
11	"	2.95	29.5	+
12	"	2.90	29.0	-
13	"	2.95	29.5	+
14	"	2.90	29.0	-
15	"	2.95	29.5	+
16	"	2.90	29.0	+
17	"	2.85	28.5	+
18	"	2.80	28.0	-
19	"	2.85	28.5	+
20	"	2.80	28.0	+

$$E_{50} = 29.63 \text{ kg-cm}$$

*Burn, smell, smoke but no rupture

TABLE 4 (cont'd)

NPN

40.4% He, 59.6% A

Sample Volume .03 cc

Sample Temperature 69°F

Ambient Temperature 80°F

Test No.	Height (cm)	Weight (kg)	Energy (kg-cm)	Result
1	20	4.0	80	+
2	"	3.5	70	-
3	"	3.7	74	-
4	"	3.9	78	+
5	"	3.8	76	+
6	"	3.7	74	-
7	"	3.8	76	+ *
8	"	3.8	76	-
9	"	3.9	78	-
10	"	4.0	80	-
11	"	4.1	82	+
12	"	4.0	80	+ *

$$E_{50} = 78.3$$

*Burn, smell, smoke but no rupture

TABLE 4 (cont'd)

NPN

Air

Sample Volume .03 cc

Sample Temperature Variable

Ambient Temperature 77°F

1.	16.0	Kg-cm	+	11.	17.5	Kg-cm	+
2.	15.5	"	-	12.	17.0	"	+
3.	16.5	"	+	13.	16.5	"	-
4.	16.0	"	-	14.	17.0	"	-
5.	16.5	"	-	15.	17.5	"	+
6.	17.0	"	+	16.	17.0	"	-
7.	16.5	"	-	17.	17.5	"	-
8.	17.0	"	-	18.	18.0	"	+
9.	17.5	"	+	19.	17.5	"	-
10.	17.0	"	-	20.	18.0	"	+

$$E_{50} = 16.95$$

Temp. = 77.0°F

1.	15.	Kg-cm	-	11.	15.	Kg-cm	+
2.	16.	"	-	12.	14.5	"	+
3.	17.	"	+	13.	14.0	"	+
4.	16.5	"	+	14.	13.5	"	-
5.	16.	"	+	15.	14.0	"	-
6.	15.5	"	-	16.	14.5	"	+
7.	16.	"	+	17.	14.0	"	-
8.	15.5	"	+	18.	14.5	"	-
9.	15.	"	-	19.	15.	"	-
10.	15.5	"	+	20.	15.5	"	-

$$E_{50} = 15.13$$

Temp. = 99 ± 1°F

1.	11.	Kg-cm	+	11.	13.	Kg-cm	-
2.	10.5	"	-	12.	13.5	"	+
3.	11.	"	-	13.	13.	"	+
4.	11.5	"	+	14.	12.5	"	+
5.	11.	"	+	15.	12.	"	+
6.	10.5	"	-	16.	11.5	"	-
7.	11.	"	-	17.	12.	"	+
8.	11.5	"	-	18.	11.5	"	-
9.	12.	"	-	19.	12.	"	+
10.	12.5	"	-	20.	11.5	"	+

$$E_{50} = 11.75$$